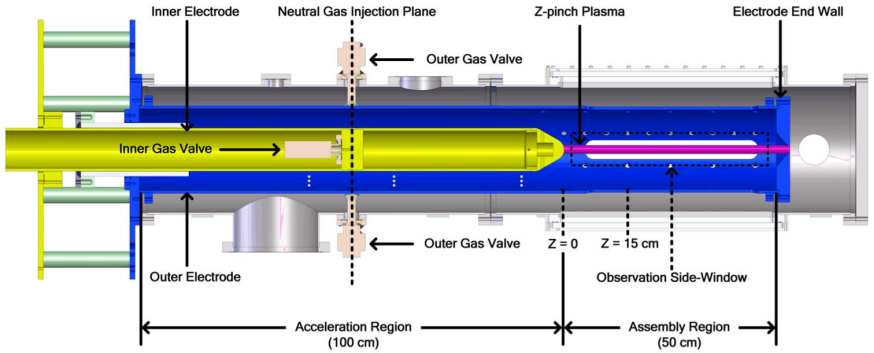
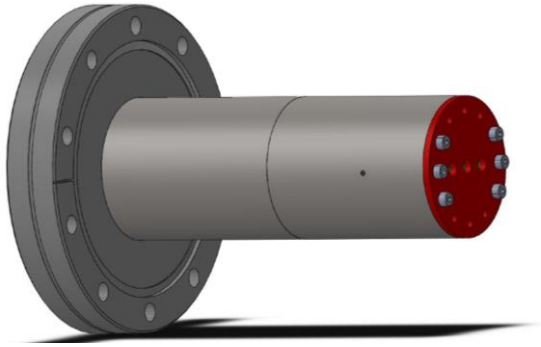
Multi-energy heads for SXR-T_e(t) measurements at FuZe

FUSION Diagnostics Program Review (Virtual)
March 5, 2021

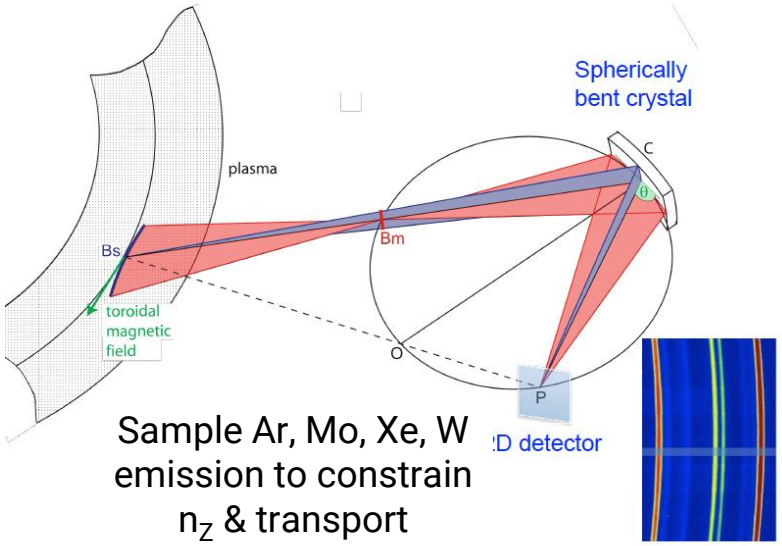




Luis F. Delgado-Aparicio, Brent Stratton and Phill Efthimion, **PPPL**
Brian Nelson, Tobin Weber, Yue Zhang, Anton Stepanov, and
Uri Shumlak, **ZAP Energy Inc.**

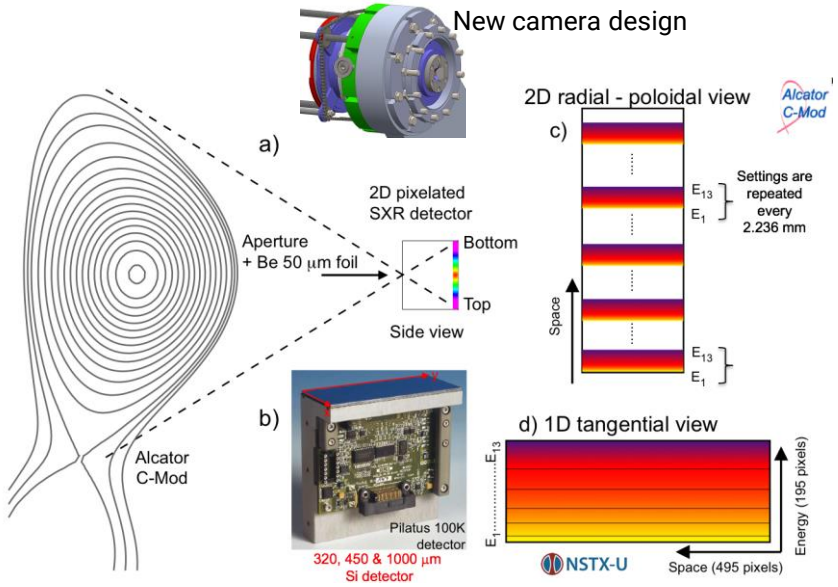
X-ray team @ PPPL has long tradition building SXR & HXR imaging diagnostics for magnetically confined fusion plasmas…, what's next?

① Medium & high-resolution x-ray imaging crystal spectrometer (XICS) for T_i, $v\phi$, n_Z, δZ_{eff} profile measurements

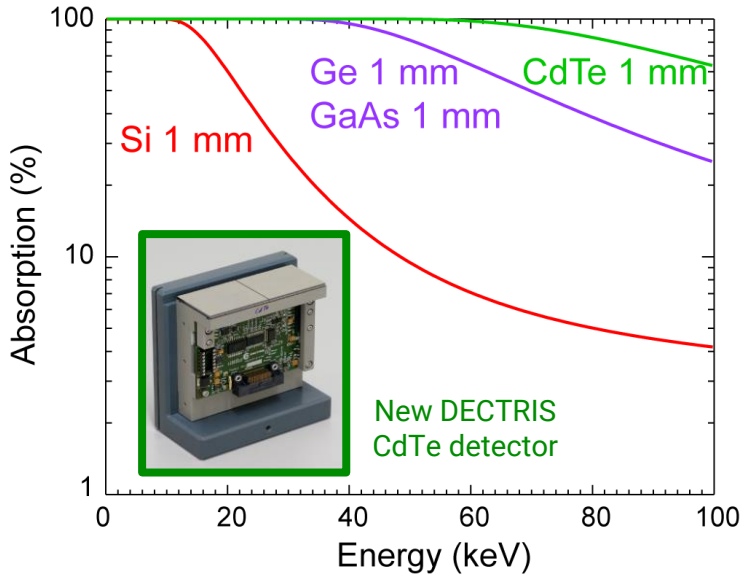


Sample Ar, Mo, Xe, W emission to constrain n_Z & transport

② Broadband multi-energy SOFT x-ray (ME-SXR) for n_Z, δZ_{eff} and T_e profile measurements



③ Broadband multi-energy HARD x-ray (ME-HXR) for T_e & $n_{e,fast}$ (RF or runaway e^-) measurements



Thermal/particle transport

- NSTX and C-Mod in USA
- KSTAR in Korea & EAST in China
- W7X in Germany
- LHD and JT60SA ('22-'25) in Japan
- ITER

T_e-measurements, MHD & Z-transport

- NSTX @ PPPL
- Alcator C-Mod @ MIT-PSFC
- MST @ UW-Madison
- WEST @ CEA in Cadarache, France
- …thinking of WHAM @ UW-Madison

Runaway e- and and RF-LHCD physics:

- MST @ UW-Madison
- WEST @ CEA in Cadarache, France

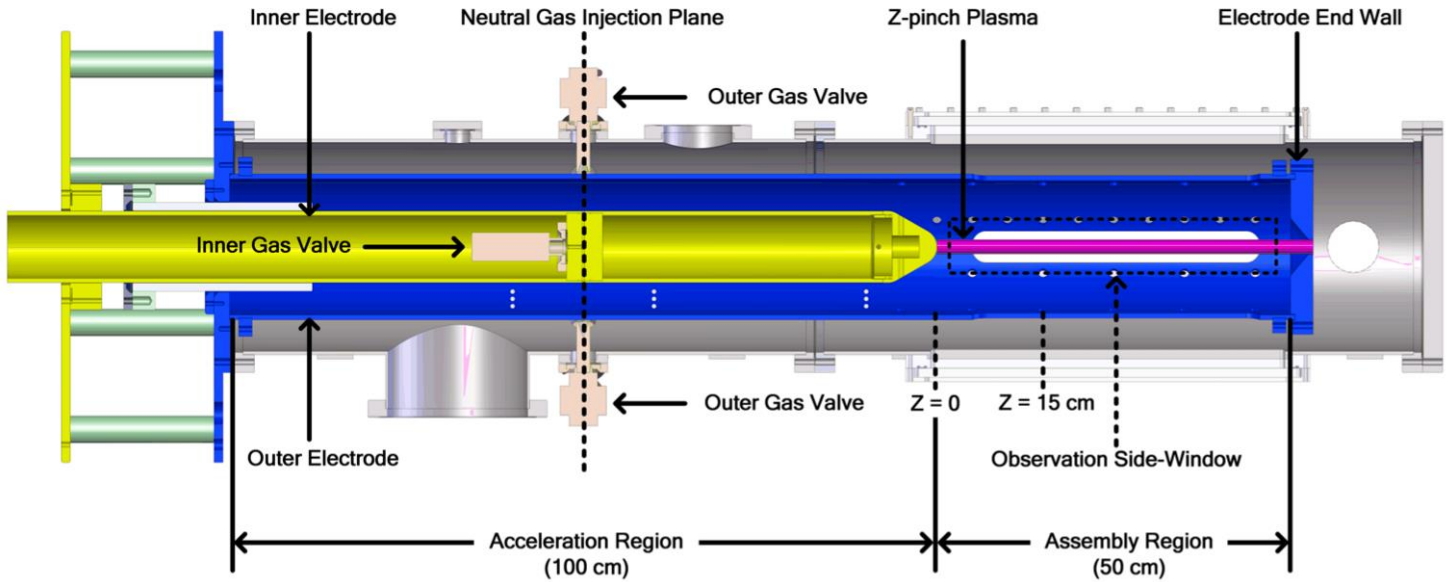
GOAL: SXR-inferred central temperature measurements @ FuZe

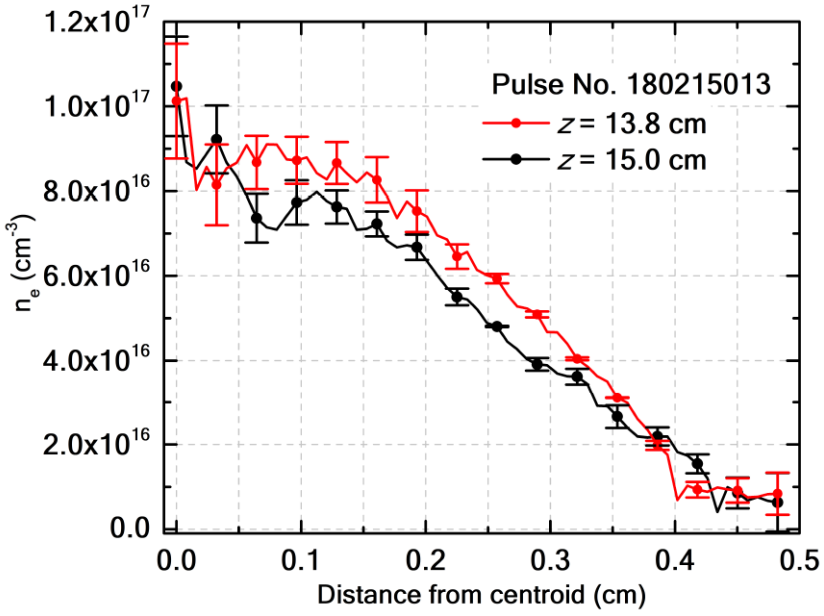
FACTS:

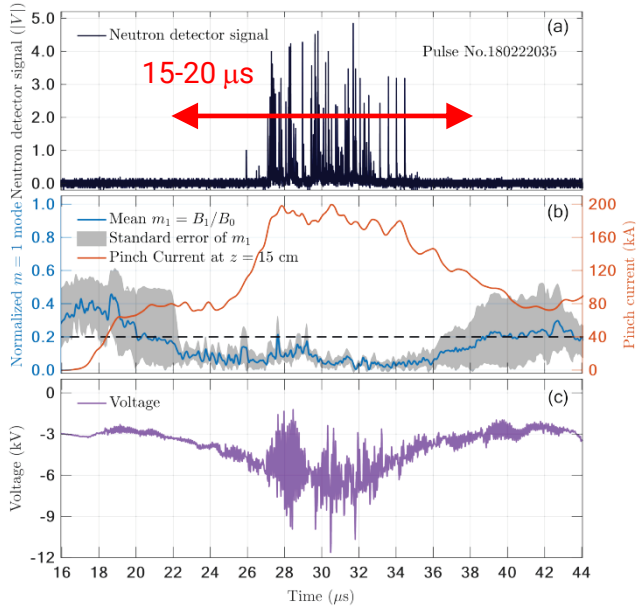
1. Good density profile measurements ~ 1-10×10^{22} m^{-3}
2. Core T_C~1-2 keV from CV triplet Doppler broadening.
3. 2.5 MeV n's are emitted over an axial extent of ~33 cm
4. End of inner electrode is graphite (no medium- to high-Zs)

GOALs:

1. **1yr project**: First time-resolved $T_{e,0}$-measurement (single point in (R,θ,z) with 1-10 μs resolution) based on multi-energy technique.
2. Infer Z_{eff}.

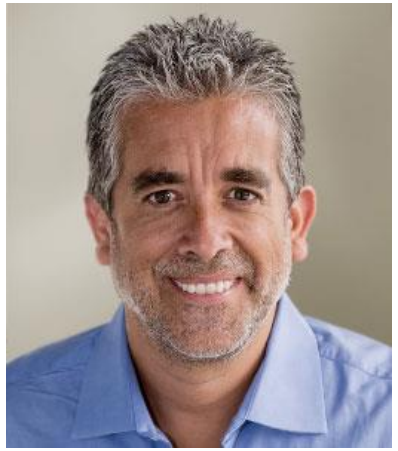




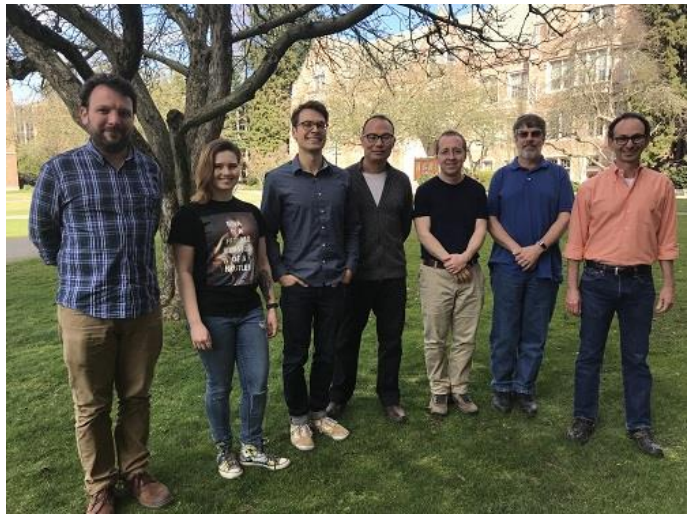


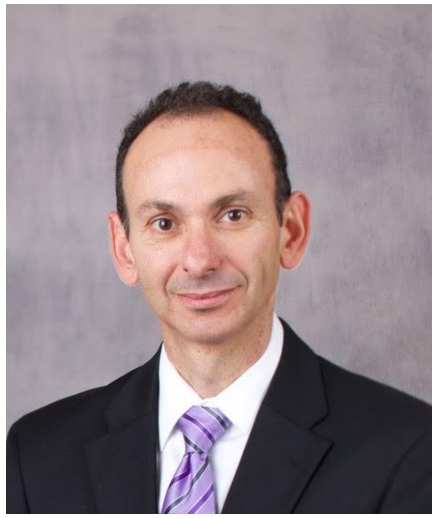
CHANGING WHAT'S POSSIBLE

Team members



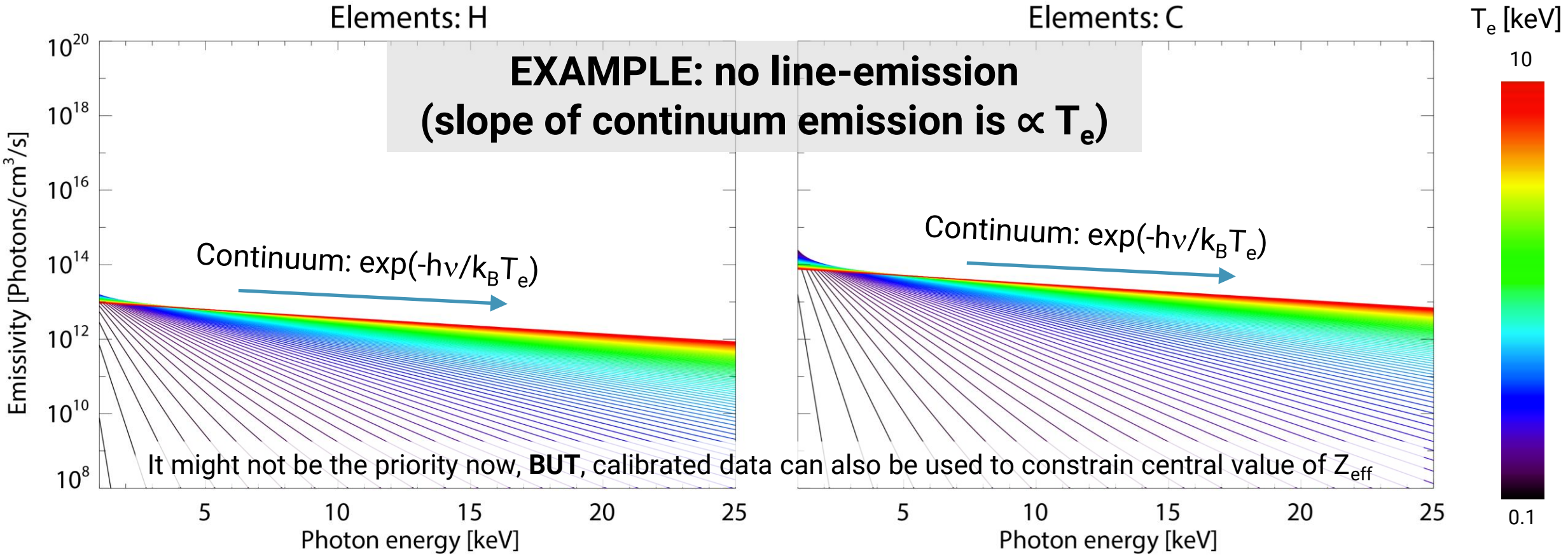
- Luis F. Delgado-Aparicio and Brent Stratton, PPPL
  - Design vacuum enclosure
  - Physics modeling
  - Purchase most of parts
  - Calibration
  - Data collection and analysis





- Brian Nelson, Tobin Weber, Anton Stepanov, Yue Zhang, Uri Shumlak, ZAP Energy Inc.
  - Design vacuum enclosure
  - Built ME-SXR heads
  - Provide port-space
  - Electrical shielding
  - Data interface and acquisition
  - Analysis

METHOD: consider energy-dependence of continuum emission to measure central temperature @ FuZe



It might not be the priority now, **BUT**, calibrated data can also be used to constrain central value of Z_{eff}

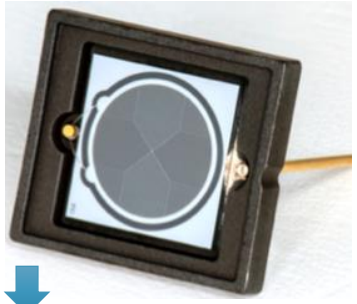
Based on our experience the least # of points in energy space you must use for constraining $T_{e,0}$ is 3-4; we have used as low as 3 and as many as 13!

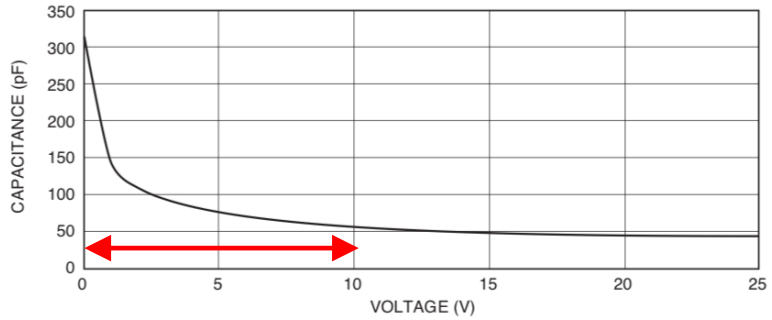
arpa·e
CHANGING WHAT'S POSSIBLE

Main components: $T_{e,0}$ measurement using metal filters (Be), fast and efficient diodes (…better than scintillators) and high-quality TIAs

① **Detectors in photon-couting mode: NO**
② **Detectors in current mode (power deposited): YES**

- Avoid detector arrays with common anodes (RF pick up)
- High efficiency - direct conversion (NO scintillators)
- Better payback for our $ (well supported thick metal filters)
- Absolutely calibrated between 0.3-30 keV
- Good time resolution (down to a μs or below)
- Excellent low-noise TIAs: $10^3 \rightarrow 10^{11}$ V/A
- Use of uninterrupted power supplies (UPS – 110V)



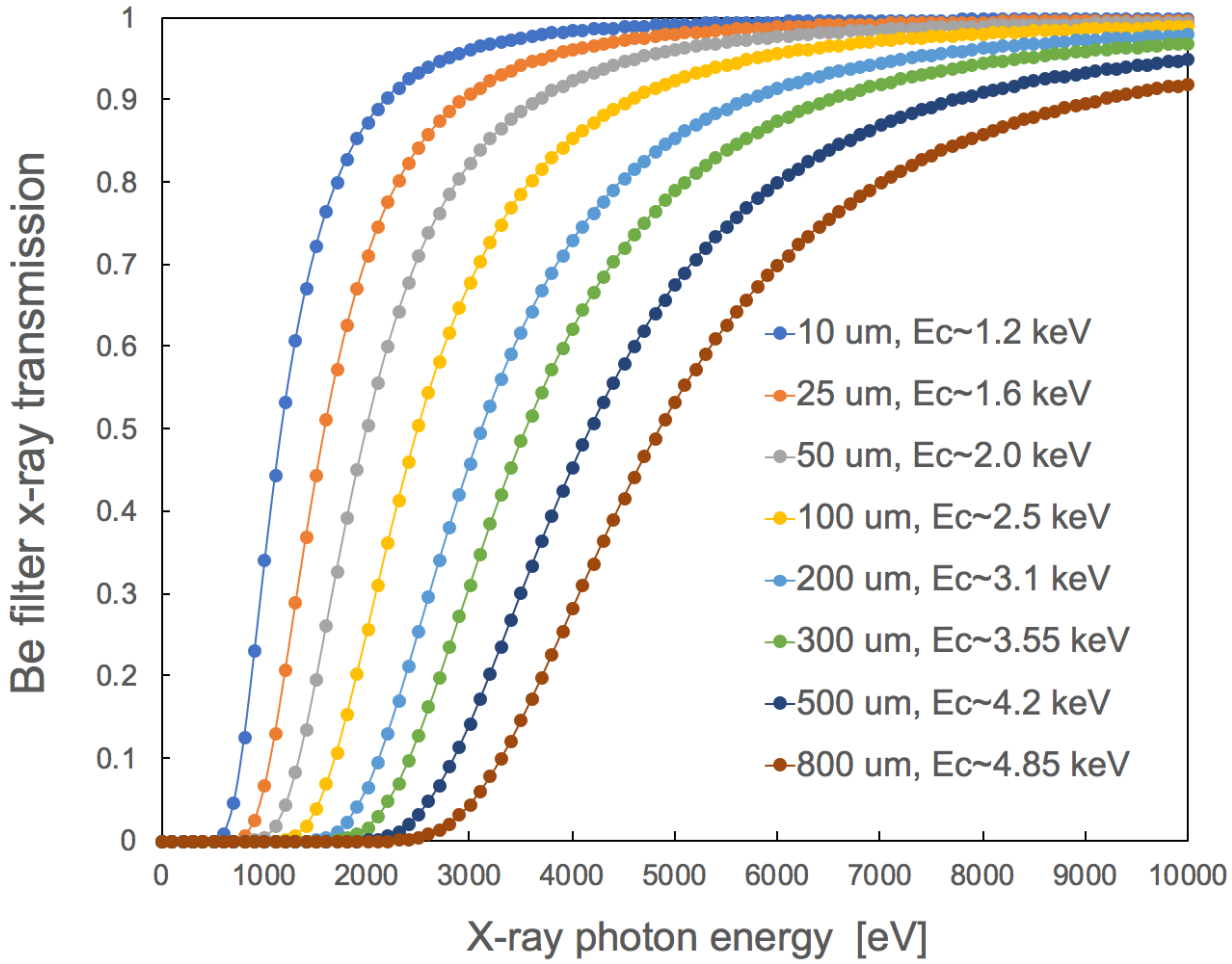


- ~ 20 mm², 300 pF, t_{rise}~3.5 ns

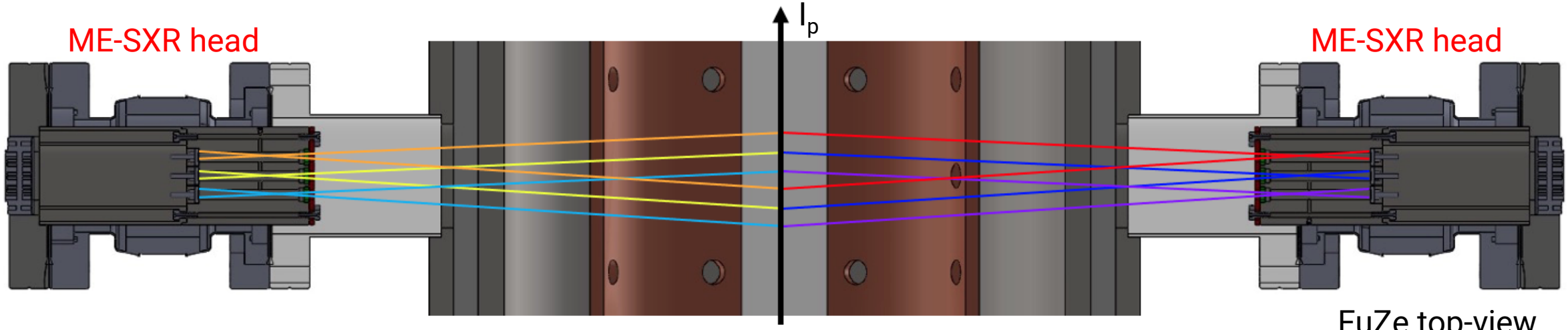
- TIA gains from 10^2 to 10^8 V/A
- Bandwidth up to 200 MHz

Typical SXR transmission through metallic filters

- Center for x-ray optics (CXRO) - LBNL
- L. Delgado-Aparicio, et al., RSI, **81**, 10E303, (2010).



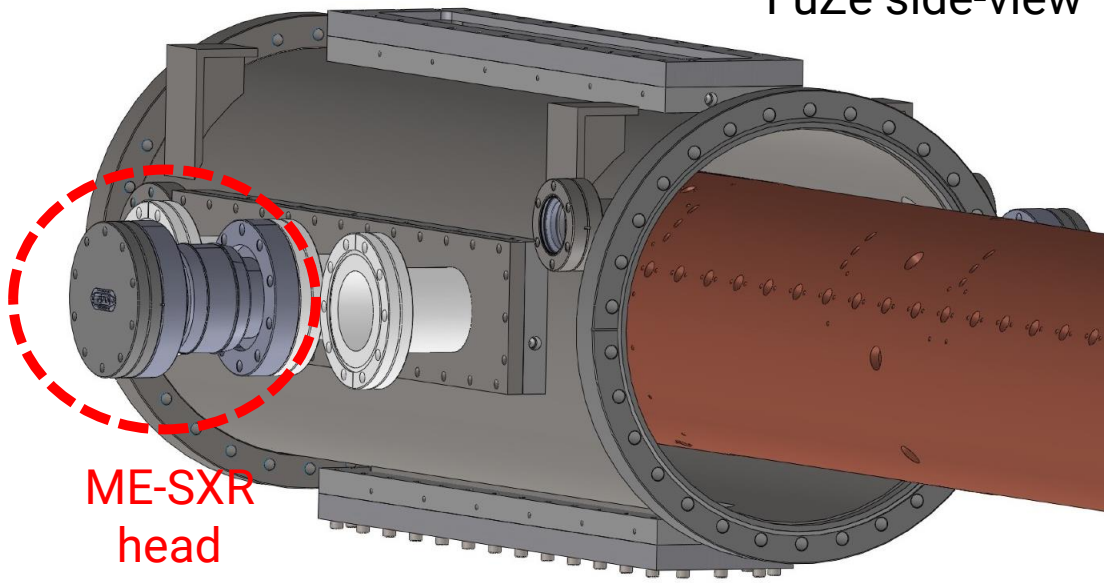
Concept is adaptable to any machine as-long-as measured emission stems from the same plasma volume (avoid beam-target emission)



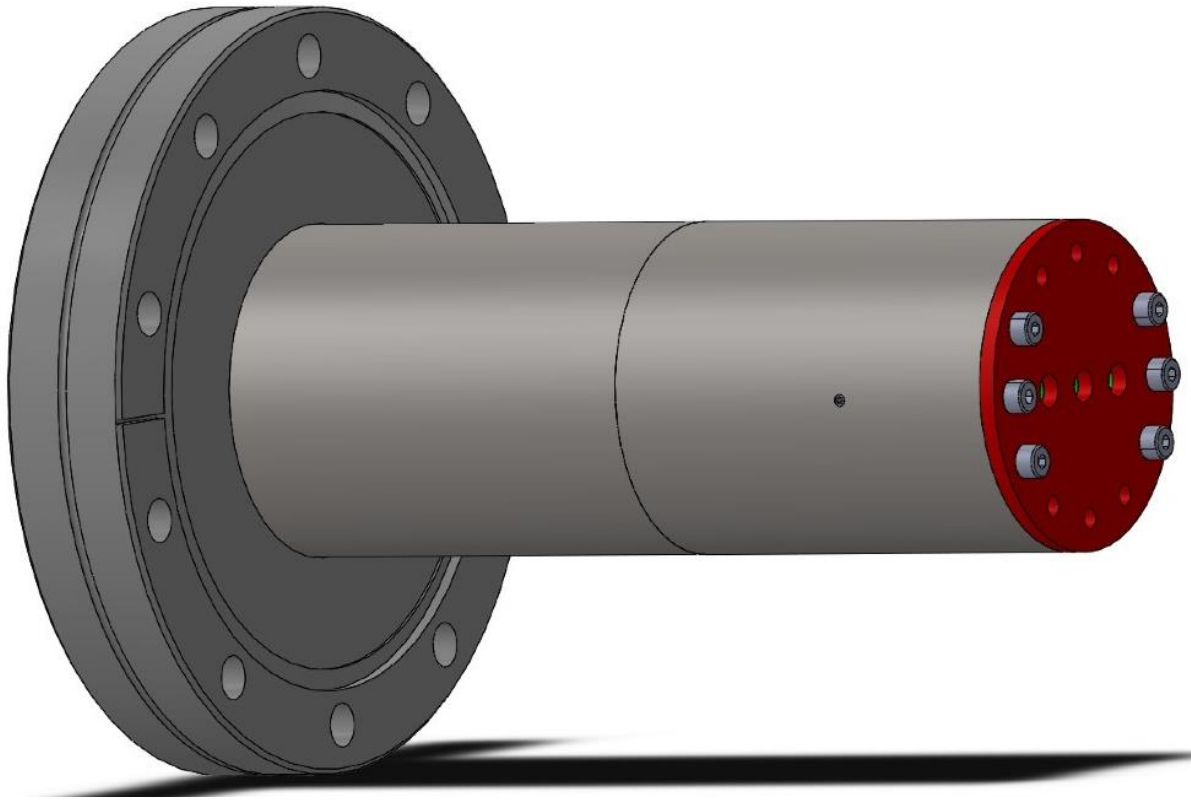
FuZe top-view

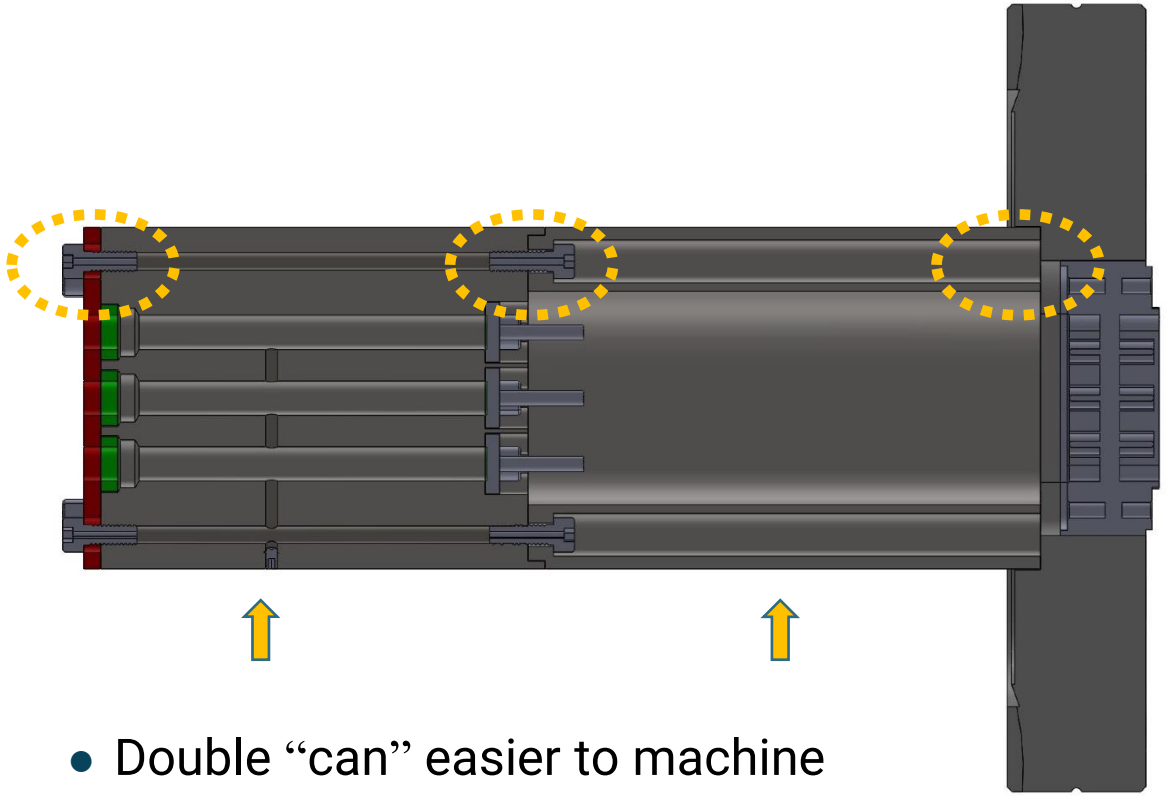
- Each SXR-head (~6” long, 4-5 pounds) installed directly on 4-5/8” nipple flange provided by ZAP-energy
- Ceramic break + CF with electric feedthroughs + 3-coaxial air-side connector
- Two sets of diodes view same plasma volume (± few cms; “identical” views)
- Up to six diode-filter combo ($\Delta E \sim 0.5$ keV) for $T_{e,0}$-measurements will improve fitting accuracy
- Six Be-10 mm filters have also been purchased for auto-calibration

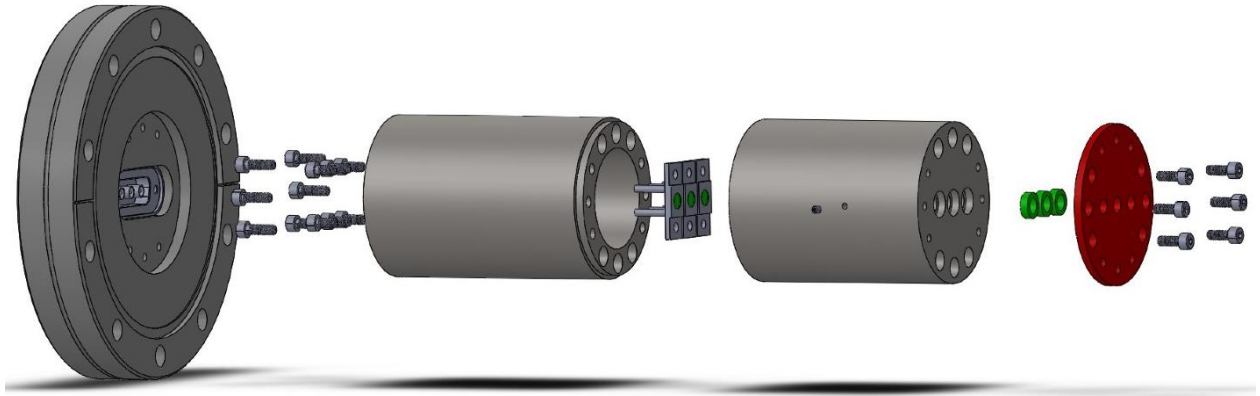
FuZe side-view



After few iterations, design effort considered a double can with components properly supported and baffled (light-tight enclosure)







- Double “can” easier to machine
- All screws vented ✓
- Side baffle (with screw) will vent interior ✓
- Lid and pocket secures integrity of Be filters
- Thick filters mounted in SS frame
- 0.01’’ fit for can, ceramic pieces, and filters

FuZe is being rebuilt @ ZAP energy and ME-SXR “heads” will be built, calibrated and tested during the Spring 2021

1) Have made significant progress in the design and construction of the ME-SXR “head” to be installed at FuZe

2) Elegant design took into consideration, physics, engineer, vacuum, magnetic, electrical & light-tight constraints/recommendations

3) UW/ZAP was in charge-of:
   - Machine body of vacuum housing + Ni-platting and purchase ceramic breaks with 4-5/8” CF
   - LED + function generator + oscilloscope for in-situ tests and calibration
   - Providing coax. cabling + 5-channel of DAQs @ 1 Mhz

4) IP agreement was signed by all parties. At this junction - of the COVID-19 crisis – we will resume installation plans after FuZe is rebuilt @ ZAP energy.

5) **ME-SXR heads can become a routine/travelling diagnostic for machines sponsored by ARPAe.**

6) **X-ray group @ PPPL will like to explore complementary 2D option @FuZe using gated photon-counting 2D PILATUS3/EIGER detectors already tested in tokamaks and stellarators**